# ANALYSIS OF THE THERMAL CROSS SECTION OF THE CAPTURE REACTION $^{13}$C(n,$\gamma$)$^{14}$C

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*Abstract:* We investigate the thermal cross section of the reaction $^{13}$C(n,$\gamma$)$^{14}$C which takes place in the helium burning zones of red giant star as well as in the nucleosynthesis of Inhomogeneous Big Bang models. We find that we can reproduce the experimentally known thermal capture cross section only if we take into account a strong hindrance of the E1 transition in the nuclear interior. This effect can be explained by the strong coupling to the giant dipole resonance.

## 1 Introduction

The neutron capture reaction $^{13}$C(n,$\gamma$)$^{14}$C plays an important role in nuclear astrophysics. In stellar helium burning it can act as neutron poison for the slow neutron capture process (s–process). As one of the main products of the CNO–cycle $^{13}$C is also abundant in helium burning zones. In low mass asymptotic giant branch (AGB) stars the reaction $^{13}$C($\alpha$,n)$^{16}$O is considered to be the main source of neutron production. In this case the capture $^{13}$C(n,$\gamma$)$^{14}$C can reduce not only the neutron but also the $^{13}$C abundance [1].

Furthermore the reaction is also important in the nucleosynthesis of Inhomogeneous Big Bang models. In neutron–rich zones intermediate–mass nuclei might be produced via a reaction sequence passing through the neutron capture reactions $^{12}$C(n,$\gamma$)$^{13}$C(n,$\gamma$)$^{14}$C [2].

In Section 2 we will present the methods used to determine the reaction cross section. Then we will discuss the experimental and theoretical input parameters for our calculations in Section 3. In Section 4 we will consider the characteristics of the s–wave capture which will lead us to the use of a semidirect model. Finally we will summarize and discuss our results in Section 5.

## 2 Calculation of the Cross Section

The thermal cross section is, if there is no resonant contribution, given by direct s–wave capture. We calculate the direct capture (DC) cross section in a potential model described in [3, 4, 5]. The total nonresonant cross section $\sigma_{\rm nr}$ is determined by the direct capture transitions $\sigma_i^{\rm DC}$ to all bound states with the single particle spectroscopic factors $C^2S_i$ in the final nucleus:

$$\sigma^{\rm DC}_{\rm tot} = \sum_i (C^2S)_i \sigma_i^{\rm DC} \quad . \tag{1}$$

The DC cross sections $\sigma_i^{\mathrm{DC}}$ are determined by the overlap of the scattering wave function in the entrance channel, the bound–state wave function in the exit channel and the multipole transition–operator.

The most important ingredients in the potential model are the wave functions for the scattering and bound states in the entrance and exit channels. For the calculation of these wave functions we use real folding potentials which are given by [4, 7]

$$V(R) = \lambda\, V_{\mathrm{F}}(R) = \lambda \int\int \rho_a(\mathbf{r}_1)\rho_A(\mathbf{r}_2)\, v_{\mathrm{eff}}\,(E, \rho_a, \rho_A, s)\, \mathrm{d}\mathbf{r}_1 \mathrm{d}\mathbf{r}_2 \quad , \tag{2}$$

with $\lambda$ being a potential strength parameter close to unity, and $s = |\mathbf{R}+\mathbf{r}_2-\mathbf{r}_1|$, where $R$ is the separation of the centers of mass of the projectile and the target nucleus. The density can been derived from measured charge distributions [8] and the effective nucleon–nucleon interaction $v_{\mathrm{eff}}$ has been taken in the DDM3Y parametrization [7]. The imaginary part of the potential is very small because of the small flux into other reaction channels and can be neglected in most cases involving neutron capture by neutron–rich target nuclei.

# 3 Determination of the Nuclear Input Parameter

The input parameters for direct s–wave capture transitions of the reaction $^{13}$C(n,$\gamma$)$^{14}$C are listed in Table 1. The spectroscopic factors are important input parameters. They can be obtained experimentally from single–particle transfer reaction studies. In our case we have used the spectroscopic factors obtained from the reaction $^{13}$C(d,p)$^{14}$C [9] for the s–wave transitions to the $0^+$ state at 6.59 MeV and to the $2^+$ state at 7.01 MeV in $^{14}$C. The spectroscopic factor for the s–wave transition to the ground state of $^{14}$C is taken from a shell–model calculation [10].

Table 1: Considered s–wave transitions for the direct contribution to the reaction $^{13}$C(n,$\gamma$)$^{14}$C. The spectroscopic factor for the ground state transition is taken from the shell model calculation of Ref. [10], while the spectroscopic factors for the other transitions are from a $^{13}$C(d,p)$^{14}$C experiment [9].

| $J^\pi$ | $E_x$ (MeV) | Q–value (MeV) | transition | $C^2S$ |
|---|---|---|---|---|
| $0^+$ | 0.000 | 8.176 | s→1p$_{1/2}$ | 1.734 |
| $0^+$ | 6.589 | 1.587 | s→2p$_{1/2}$ | 0.14 |
| $2^+$ | 7.012 | 1.164 | s→2p$_{3/2}$ | 0.065 |

The potential strength parameter $\lambda$ for the bound state is adjusted to the known binding energies. In the scattering state we determine $\lambda$ from the scattering lengths. For neutron scattering on $^{13}$C the free scattering lengths are given by $a_{\mathrm{c}} = 5.76$fm and $a_{\mathrm{i}} = -0.48$fm, where the subscript c and i denote the coherent and incoherent scattering length, respectively. Since the incoherent scattering is not negligible in this case we determine two different potentials for the channel spins $J_{\mathrm{a}} = 0$ and $J_{\mathrm{a}} = 1$, which are $\lambda_0 = 1.1396$ and $\lambda_1 = 1.2465$, respectively.

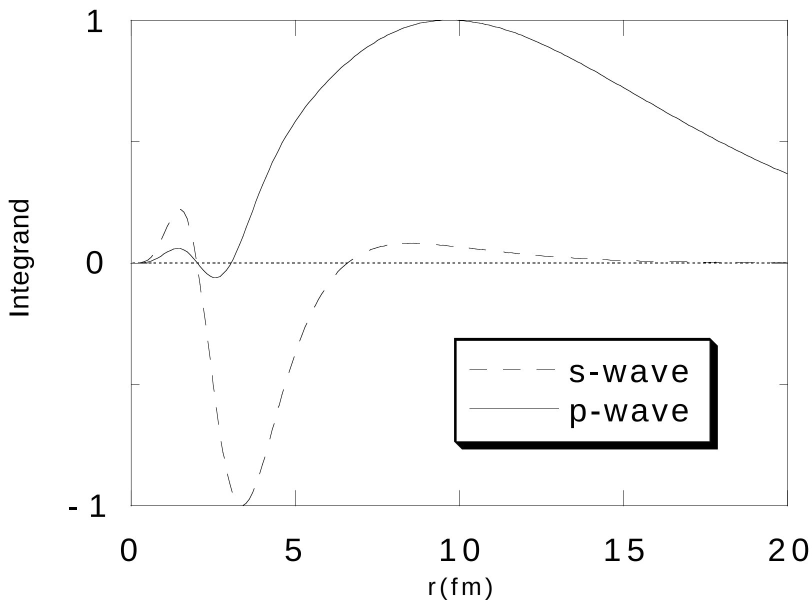


Figure 1: The radial integrand for the direct capture of thermal s–wave capture and p–wave capture at the thermonuclear energy $E = 10$ keV.

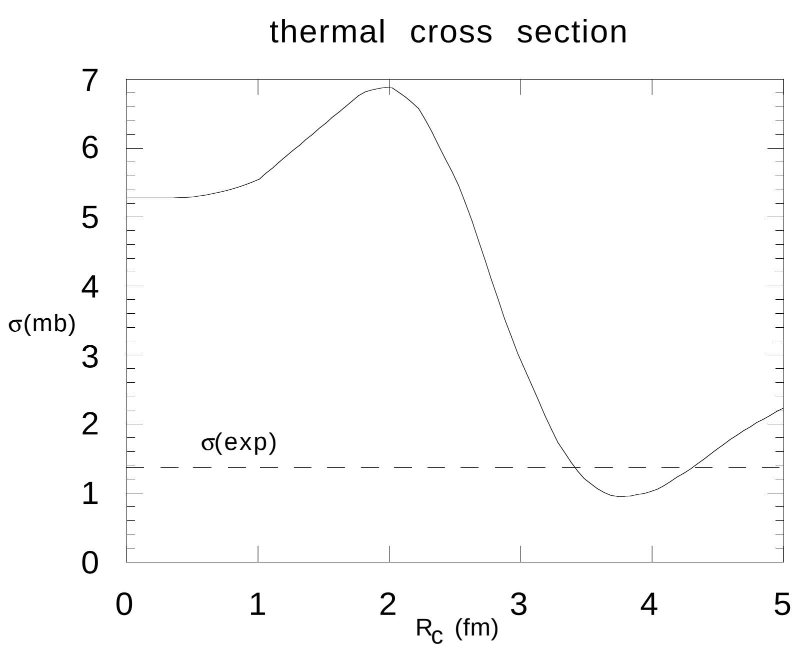


Figure 2: The dependence of the thermal s–wave cross section on the cutoff radius $R_c$ in the cutoff model. We compare the cross section with the known thermal cross section of 1.37 mb.

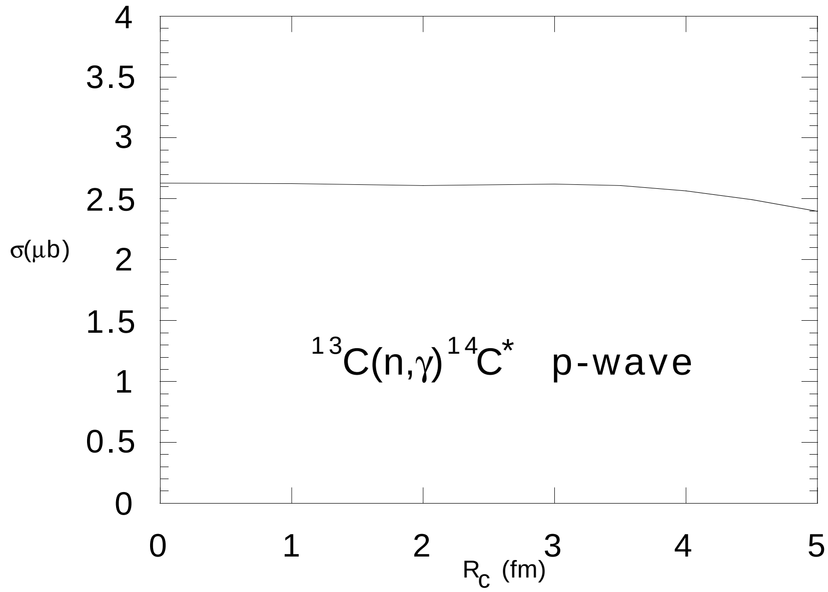


Figure 3: Dependence of the thermonuclear p–wave capture cross section on the cutoff radius $R_c$ in the cutoff model.

# 4 The Thermal Capture Cross Section

The thermal s–wave capture cross section is clearly dominated by the transition to the ground state of $^{14}$C. The other two transitions are negligible due to the much lower spectroscopic factors and the higher excitation energies. Using the data of Table 1 we obtain a thermal capture cross section of 5.28 mb, clearly higher than the measured value of 1.37 mb. In order to understand this discrepancy we look at the direct–capture radial integrand of this transition. From Fig. 1 we see that major contributions come from the nuclear interior. The maximum of the integrand is at around 3.4 fm which is close to the surface of the nucleus. We compare this with the integrand of the p–wave transition to the first excited state at an incident energy of 10 keV. In this case the most important contributions come from the nuclear exterior. The maximum of the integrand lies at approximately 10 fm.

In the nuclear interior both the scattering and the bound state wave function are modified due to the coupling to the giant dipole resonance. This coupling causes a hindrance of the E1 capture cross section at low energies. These effects were discussed by several authors, usually at higher energies [12, 13]. If the neutron energies is close to the energy of the giant diploe resonance the coupling is attractive causing an increase of the cross section. In order to estimate the influence of this effect on our reaction we use the simple cutoff model from Ref. [13]. In this model an effective charge

$$e_{\text{eff}}(r) = e_{\text{E1}}\theta(r - R_c) \tag{3}$$

where $e_{\text{E1}}$ is the equal to $-Ze/A$ for neutron capture and $R_c$ is a cutoff radius. Inside this cutoff radius the effective charge vanishes.

In Fig. 2 the dependence of the s–wave capture cross section at thermal energies on the

cutoff radius is shown. While the cross section is clearly too high for a small cutoff radius, it is very close to the experimental thermal cross section of 1.37 mb if the cutoff radius is around 4 fm. This is very near to the nuclear radius. On the other hand the thermonuclear p–wave capture does not show a strong dependence on the cutoff radius (see Fig. 3).

# 5 Summary and Discussion

We have shown that the thermal cross section of the reaction $^{13}$C(n,$\gamma$)$^{14}$C can be well described in a potential model if one takes into account the coupling of the wave functions to the giant dipole resonance in the nuclear interior. This effect causes a strong hindrance of the E1 capture cross sections if the main contributions to the direct capture integrand come from the nuclear interior. This is especially the case for incoming s–waves.

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